Calibration of GOES Imager Visible Channels

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***Abstract*—Four options for the post-launch calibration of GOES-Imager visible channel were examined, including those based on the EDF, on desert measurements, on star observations, and on MODIS data. The basic assumptions and methodologies of these options were summarized in this paper, as well as major advantages and disadvantages, from both theoretical and operational perspectives. These discussions provide a basis for further evaluation of these and other methods, with the goal of selecting an operational post-launch calibration algorithm that incorporates the strength of all the methods.**

Keywords-vicarious calibration; sensor degradation; GOES; MODIS; EDF; visible channel.

I. INTRODUCTION

The National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) operates the U. S. “weather satellites”, which include the Geostationary Operational Environmental Satellite (GOES). The visible channel of the GOES Imager instrument does not have onboard calibration device. It is therefore necessary to calibrate this channel vicariously using external references to correct for the sensor degradation over time.

Several options exist for the vicarious calibration of GOES Imager visible channel. Four options, each uses a different external reference, have been examined at NOAA/NESDIS Office of Research and Applications. This paper offers a briefly overview and preliminary evaluation of these options. The goal is to design an operational algorithm for the GOES Imager visible channel calibration that makes the best use of the strength of these and any other methods for the optimal performance.

II. FOUR CALIBRATION OPTIONS

A. EDF-Based Calibration

This method was inspired by an experiment of calibrating the visible images from the Geostationary Meteorological Satellite (GMS) [1]. The fundamental assumption is that the statistical distributions of reflectance over certain area does not change over time, therefore any drift in those distributions is attributed to sensor degradation. NOAA has been studying this option since 1998 in conjunction with the Empirical Distribution Function (EDF) developed in another application [2], as summarized by Crosby et al recently [3].

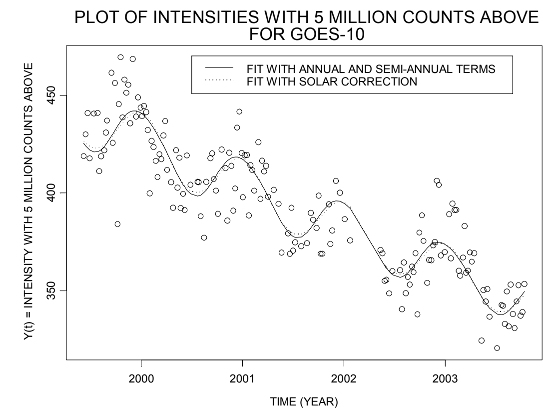

Figure 1: Digital counts, plotted as a function of time, of the five millionth brightest pixel values from the GOES-10 Imager visible channel.

Figure 1 shows the results of this method applied to the GOES-10 full disk images. One of the difficulties of applying the EDF analysis to the GOES data is that the number of space views in a full disk image varies as the satellite oscillates around its nominal geostationary location and the sensor adjusts its attitude. The unstable number of space views introduces change in EDF even in the absence of sensor degradation. To avoid that complexity, the statistics on the bright side of the EDF is monitored, instead of the entire EDF.

It was further discovered that the EDF typically has annual and semiannual variation, in addition to the long term decline. It is concluded that the long term decline is largely caused by sensor degradation, the annual variation is related to variation of the sun-earth distance, and the semiannual variation may arise from internal dynamic processes of the earth-atmosphere system such as the seasonal variation of cloud amount and preferred location. While may be of interest to other scientists, the semiannual variation is a source of noise in calibration. It was found that the five millionth brightest pixel (out of the total of over 225 millions) is a good compromise for GOES-10 between sufficient sensitivity in EDF analysis and minimal semiannual variation.

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The EDF-based calibration can be carried out with weekly collection of the EDF of one full disk image. The full disk image is a widely available operational product, its EDF is only a few kilobytes in size. From the point of view of satellite operation, this is possibly the most reliable and cost-effective way of calibration.

The most serious drawback of the EDF-based calibration is its assumption that the statistical distributions of regional reflectance are invariant in time. In theory, this assumption prevents any data calibrated with this method from being used in most climate studies. The validity of this assumption may depend on the location, size, and the time scale of the region. The choice of global scenes by Crosby et al [3] should be more robust statistically, on the other hand it may increase the uncertainty associated with viewing geometry. In practice, the condensed EDF data are small and easy to analyze but they cannot be used to answer many questions that may arise later in research, for example the location and the viewing geometry of the pixels under examination.

B. Desert-Based Calibration

The desert-based calibration is adapted from a similar method developed for the vicarious calibration of the visible and near infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA's Polar-orbiting Operational Environmental Satellite (POES) [4]. The premise of this method is that the radiance from certain stable earth targets such as desert is invariant in time and therefore can be used for calibration. Rao and Zhang [5] later adapted this method to calibrate the GOES Imager visible channel. Wu and Sullivan [6] further improved the method by introducing a sinusoidal term in addition to the linear degradation to capture the intra-annual variation of the signal.

Figure 2 illustrates this method with a time series of GOES-8 measurements (digital counts with proper corrections for space count, earth-sun distance, and solar zenith angle) over the Grand Desert in Sonora, Mexico. These measurements, which are proportional to radiance using a fixed calibration such as that obtained during pre-launch tests, show a pattern of steady decay superimposed with a seasonal variation. The steady decay is largely caused by instrument degradation. The seasonal cycle, on the other hand, is primarily caused by the local bidirectional reflectance distribution function (BRDF), i.e., the variation of surface reflectance associated with the annual cycle of solar zenith angle.

The desert-based method requires minimal effort in data collection (once per day per satellite and each dataset is only a few kilobytes). The data analysis is also straightforward. With the additional sinusoidal term, the long term degradation can be separated and identified.

One of the major difficulties with this method is that the data display intra-annual variation that is larger than the inter-annual variation. Because of this, estimate of instrument degradation shortly after launch (~18 months) is less accurate, in fact erroneous estimate of degradation can be made if the intra-annual variation is not properly recognized and fully accounted for. This is a common difficulty in all desert-based

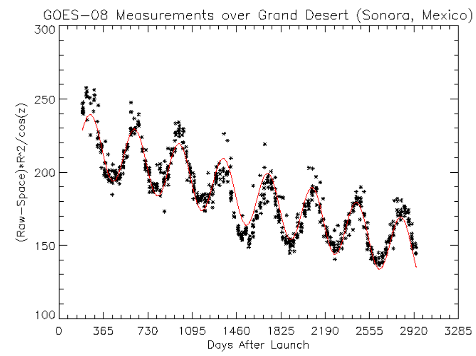

Figure 2: GOES-8 Imager visible channel measurements at local noon over Grand Desert (32N, 115W), plotted as a function of days after launch. The GOES-8 measurements are expressed in terms of normalized counts that have been adjusted for space count, solar zenith angle, and earth-sun distance.

vicarious calibration [6], but is especially so for instruments on geostationary platform since they often lack the luxury of viewing a good desert target near the nadir. As the satellite zenith angle increases (to more than 50 degrees in the case of GOES-8 viewing the Grand Desert), so does the BRDF variation in response to annual change of solar zenith angle, hence the increased difficulty in identifying the degradation from the desert observations.

Absolute calibration is another difficulty for the desert-based calibration. While the relative calibration, or the determination of degradation within a period of time, can be derived as long as the target is stable, it is unclear whether the pre-launch calibration, or any absolute calibration, is valid at any time. The reflectance of the Grand Desert was measured at nadir, which may not be the same as that observed by GOES.

As eluded before, the target stability is still of critical importance even for relative calibration. As a "living desert", the Grand Desert is subject to certain seasonal cycle in response to local climate and ecology. One may even discern that the time series in Fig. 2 seems to be consisted of two regimes before and after fall 1997 (around Day 1350, since GOES-8 was launched in April 1994). This has been related to a climate event called El NICO-Southern Oscillation (ENSO) that was active at the time [7].

C. Star-Based Calibration

GOES Imager routinely observes stars with its visible channel for orbit and attitude tracking purposes. Bremer et al [8] proposed to use those observations for radiometric calibration. Chang et al [9, 10] substantially expanded the original study, most notably the selection and processing of the star measurements. Figure 3 is an example of recent results.

The biggest advantage of the star-based calibration is signal stability. The stars used for calibration have been carefully selected and there is little doubt that the signal would change over time. Unlike the desert-based method, which is at the merci of clouds, star measurements are also highly predictable.

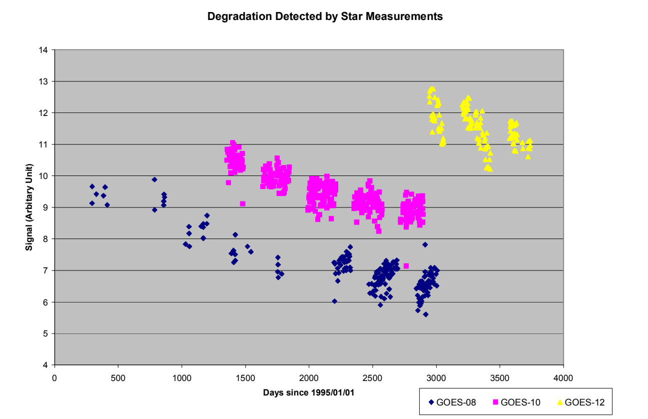

Figure 3: Radiation from a star (β-Cnc) as measured by three GOES Imager visible channels (GOES-8/10/12) plotted as a function of days since 1 January 1995.

While predictable, the availability of star measurements has its own flaws. As the geostationary satellite revolves around the earth while the earth revolves around the sun, the time of day when a satellite observes a particular star changes with the day of the year. This creates two problems. One is that for a few months of a year, the star is too close to the sun when the star observation occurs around the local midnight. For those months the star measurements are not available, thus the annual gaps in the time series.

Certain intra-annual variation is also apparent in Fig. 3, for example the downward trend for GOES-12 and the upward trend for GOES-8 that are embedded in the general downward trend of degradation. It is speculated that the large diurnal variation of the GOES Imager scan mirror (Fig. 4) causes the scan mirror distortion. When the star is observed at different time of day in different day of year, the diurnal cycle of scan mirror distortion becomes annual cycle of signal intensity.

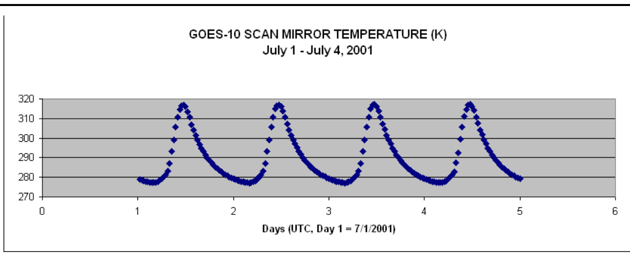

Figure 4: Example of GOES Imager scan mirror temperature variation.

Regardless of the cause, the star-based calibration has the similar difficulty that the relatively small long term degradation is embedded in the relatively large intra-annual variation. This tends to increase the uncertainty and latency of estimating instrument degradation (the latter refers to the time after launch when the degradation can be reasonably well estimated). The star-based calibration also lacks absolute calibration.

From a practical point of view, the star measurements are not readily available to most users and, since they were intended for navigation purposes, have to be carefully screened and re-processed for radiometric calibration. Great progress has been made and its potential for sensor status diagnosis is being explored.

D. MODIS-Based Calibration

The GOES Imager visible channel measurements are regularly co-located with those by a well calibrated radiometer such as the Moderate Resolution Imaging Spectroradiometer (MODIS). Since these measurements are in similar spectral interval and of similar spatial resolution, they provide an opportunity to calibrate the GOES sensor, assuming one can derive from the MODIS measurements what the GOES sensor should measure [11, 12].

Figure 4 is an example of MODIS-based calibration for GOES-12 Imager visible channel. In the upper panel, the solid line is the histogram of what GOES should measure, estimated from the MODIS measurements. The dashed line is the histogram of the actual GOES measurements. The difference indicates the calibration error. In the lower panel, the calibration error is plotted as a function of post-launch calibration correction, which has a minimum around 1.17. This means that, on that particular day (5 October 2004), one can calibrate the GOES-12 Imager visible channel measurements with the pre-launch calibration coefficients, multiplied that result by this post-launch calibration correction of 1.17, to obtain values that agree with MODIS calibration. The dashed and dotted line in the upper panel is the histogram

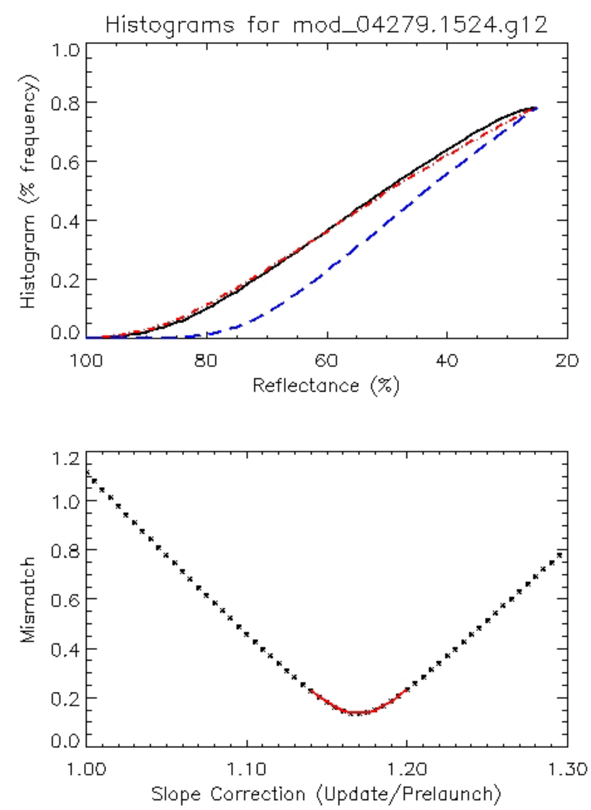

Figure 5: Illustration of GOES Imager visible channel post-launch calibration using MODIS data.

of the GOES data with corrected calibration. This can be repeated whenever the co-location is possible, and the time series of the post-launch correction can be used to estimate the sensor degradation (Fig. 6).

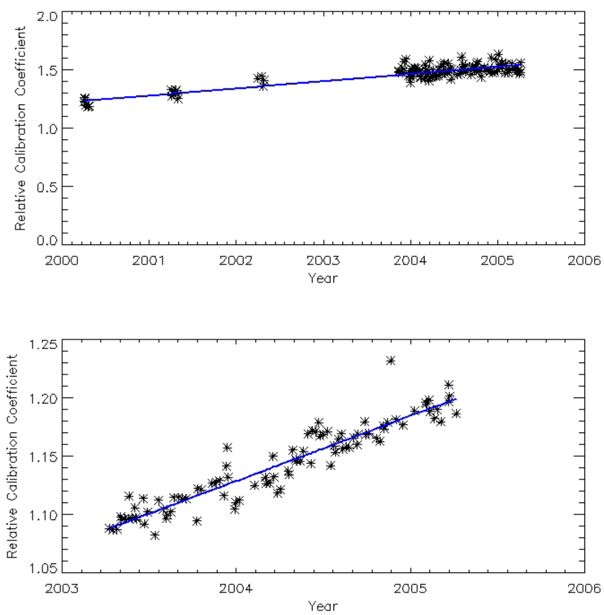

Figure 6: Time series of GOES-10 (upper panel) and GOES-12 (lower panel) Imager visible channel post-launch calibration using MODIS data.

The most significant advantage of the MODIS-based calibration is that it can provide absolute calibration with single co-location. This solves two major issues in most vicarious calibration, the establishment of an absolute reference and the latency in the post-launch calibration if the reference is expected to vary in certain pattern.

Many of the common issues in vicarious calibration still need to be addressed. This method is based on the premise that one can derive from MODIS data what GOES should measure. In addition to complete confidence in MODIS calibration, this assumption also requires careful scrutiny on how well the GOES and MODIS are co-located spatially, temporally, and spectrally [12]. From the perspective of satellite operation, the MODIS-based method requires MODIS data, which is not an operational product and its availability is out of NOAA's control. This method also requires considerably more human and computer resource to develop, maintain, and execute.

III. SUMMARY

Four methods for post-launch calibration of GOES-Imager visible channel were examined in detail at the NOAA/NESDIS Office of Research and Applications. These include those based on the empirical distribution function of earth view data, on measurements from stable earth target such as desert, on star observations, and on MODIS data. Some results from these methods are presented as examples. More details are presented in the references. Other methods, including those based on lunar observations and on radiative transfer model, have been considered but not presented here.

The basic assumption and methodology were summarized, as well as major advantages and disadvantages. Both theoretical and operational perspectives were considered in evaluating each method. These discussions lay the foundation for further comparison of these and other method, with the goal of selecting an operational post-launch calibration algorithm for GOES Imager visible channel that incorporate the strength of all the methods.

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